Dynamical Studies in Hurricane Intensity Change

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Award Number: N00014-93-1-0456 P00006
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LONG-TERM GOALS AND OBJECTIVES

The long-term goals and objectives of this research are to develop a more complete physical understanding of tropical cyclone (TC) intensity change processes. This year's work focused on the following three areas: Determining the three-dimensional asymmetric dynamics of the TC core region; Testing hurricane maximum intensity theory; Analyzing the environmental influences on the intensification of Hurricane Opal (1995). Each of these projects delivers important advances in our understanding of hurricane intensity and intensity change. The main new findings are summarized below.

Simulation and Analysis of Asymmetric Dynamics in Tropical Cyclone Cores

APPROACH

Evidence for complex, asymmetric inner-core dynamics in tropical cyclones has been observed for some time, and continues to accumulate due to the ever-increasing resolution of both observation methods (e.g., Kuo et al., 1999; Reasor et al., 2000; Kossin and Eastin, 2001) and numerical simulations (Liu et al., 1997, 1999; Braun and Tao, 2001). In the previous two years, we initiated a broad-reaching study by considering the asymmetric dynamics and stability of fully three-dimensional disturbances in fully three-dimensional, tropical cyclones. Significant results have come to fruition from this work.

WORK COMPLETED, RESULTS, IMPACT, AND APPLICATIONS

In previous years, we undertook the development of a method for studying the linearized evolution of fully three-dimensional, nonhydrostatic perturbations to three-dimensional, balanced, hurricane-like vortices. In the past year, we have improved the numerical techniques underlying this method. The results of preliminary studies have been confirmed with the improved numerics, showing that hurricane-like vortices can support low-wavenumber instabilities, and lead to substantial inner-core mixing of heat, momentum, and vorticity. These vortices also support wavenumber one instabilities similar to those studied previously by the investigators (Nolan and Montgomery, 2000; Nolan et al., 2001), which account for the frequently observed small-scale trochoidal motion of these cyclones.

Our method can also be used to simulate the linearized evolution of asymmetries introduced into the near-core environment of the tropical cyclones. Such asymmetries may be representative of localized

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**
4. TITLE AND SUBTITLE **Dynamical Studies in Hurricane Intensity Change**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Atmospheric Science,,Colorado State University,,Fort Collins,,CO, 80523**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		

14. ABSTRACT

The long-term goals and objectives of this research are to develop a more complete physical understanding of tropical cyclone (TC) intensity change processes. This year???s work focused on the following three areas: Determining the three-dimensional asymmetric dynamics of the TC core region; Testing hurricane maximum intensity theory; Analyzing the environmental influences on the intensification of Hurricane Opal (1995). Each of these projects delivers important advances in our understanding of hurricane intensity and intensity change. The main new findings are summarized below.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

bursts of convection near the core of the tropical cyclone. As our equations of motion are nonhydrostatic and non-balanced, we may consider directly the effect of the heating associated with convection, rather than assuming a predetermined vorticity or PV field. Simulations of low-wavenumber thermal anomalies in the vicinity of a weak tropical storm-like vortex show that the resulting evolution goes through two phases (see Figure 1). In the first phase, there is substantial intertia-gravity wave radiation and an adjustment to quasi-gradient wind balance. In the second phase, the resulting PV anomalies are axisymmetrized, leading to intensification of the basic-state vortex. These results confirm numerous essentially two-dimensional studies that preceded them (e.g., Carr and Williams, 1989; Montgomery and Kallenbach, 1997; Nolan and Farrell, 1999; Moller and Montgomery, 1999). However, the three-dimensionality of the system introduced some interesting new aspects to the problem. For example, the altitude of maximum intensification of the basic-state vortex seems to depend upon the radial location of the initial thermal perturbations.

In accordance with previously stated plans, we have extended our methodology to allow for the inclusion of the secondary circulation of these vortices, which can be quite substantial and is critical to the intensification process. Preliminary results with tornado-like vortices generated from a simple axisymmetric model show how unstable modes are modified by the secondary circulation and the substantial radial shear of the vertical winds in the vortex core.

FUTURE WORK

Significant work remains to bring this project to full completion. The symmeric response and resulting vortex intensification caused by the axisymmetrization process requires the development of an wave mean flow formalism for both symmetric ($n=0$) and asymmetric ($n\neq0$) perturbations. Further work is required to compute the dynamics and stability of fully three-dimensional perturbations to tropical cyclones with their secondary circulations included.

Understanding Maximum Hurricane Intensity: Resolution Sensitivity Studies

APPROACH

The Emanuel 1995a model (E95a model) was kindly provided to us by K. Emanuel. Our initial examination was to take advantage of the simple construction of the model to experiment with the addition of imposed secondary eyewalls, continuing the work of Camp and Montgomery (2001). Higher resolution was determined to be necessary to model this. In the course of this examination, a large sensitivity to model intensity was discovered to changes in model resolution. This undocumented behavior of the model became our focus for study this year. To further our investigation on this topic, we desired a more complete axisymmetric model to see if the resolution sensitivity was more general, in part motivated by the findings of Hausman (2001) in yet another axisymmetric model. The Rotunno and Emanuel (1987) model (RE87 model) was kindly provided to us by R. Rotunno for this purpose.

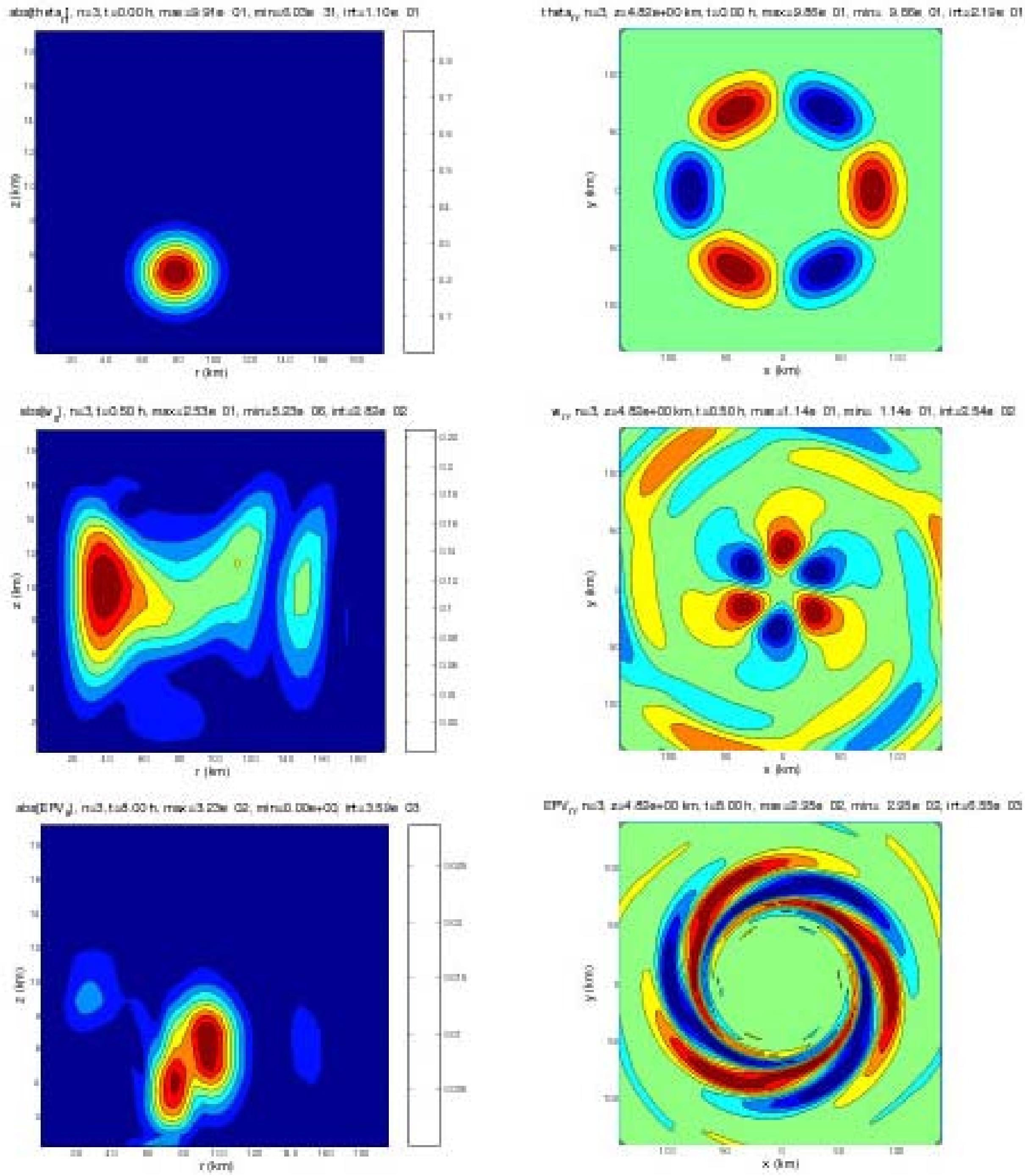

Figure 1. Linear evolution of a purely thermal perturbation near the core of a weak, baroclinic, tropical storm-like vortex. The first two plots show r-z and x-y cross-sections of the initial disturbance in θ. The next two show cross-sections depict vertical velocity at t = 30 min, showing gravity wave propagation. The last two cross-sections show perturbation PV at t = 8 h, showing interaction with the mean vortex and axisymmetrization.

WORK COMPLETED AND RESULTS

Using the E95a model, a parameter space of model resolution versus sea surface temperature was thoroughly explored. Two modes of model behavior were found and were partitioned largely by resolution. At low resolution, the model was able to achieve steady states for long periods of time, but the resulting storm intensities did not vary systematically with resolution. For surface temperatures of 27°C and maximum potential intensity (MPI) (estimated using Emanuel 95b, and elsewhere below) of 74 m/s $^{-1}$ the modeled intensity varied between 67 and 81 m s $^{-1}$. In this low resolution regime there was a larger, and again non-systematic, tendency of the intensification rate on the fifth day of the simulation (or any other day during the initial spin up period). Intensification rates could vary from 1 to 4 m s $^{-1}$ per day for a set of 27^{o}C simulations. The variation has been traced in part to the inexact way the initial vortex is represented at low resolution in the model.

The second regime of behavior of the E95a model at higher resolution (> 57 nodes) did not approach a steady state. After achieving a maximum intensity, the eyewall continued to accumulate angular momentum from the environment while the radius of maximum winds gradually expanded, and thus weakened slowly over time. Intensification rates and peak winds were more-or-less steady with increasing resolution with peak winds of approx 79 m s $^{-1}$ compared with the 74 m s $^{-1}$ MPI at 27^{o}C surface temperature.

Our investigation with the RE87 model was to change the resolution of the model for a default case. It was found that the simulated hurricane increased in intensity with increasing resolution, very greatly exceeding that found by nature or predicted by MPI theory (see Figure 2).

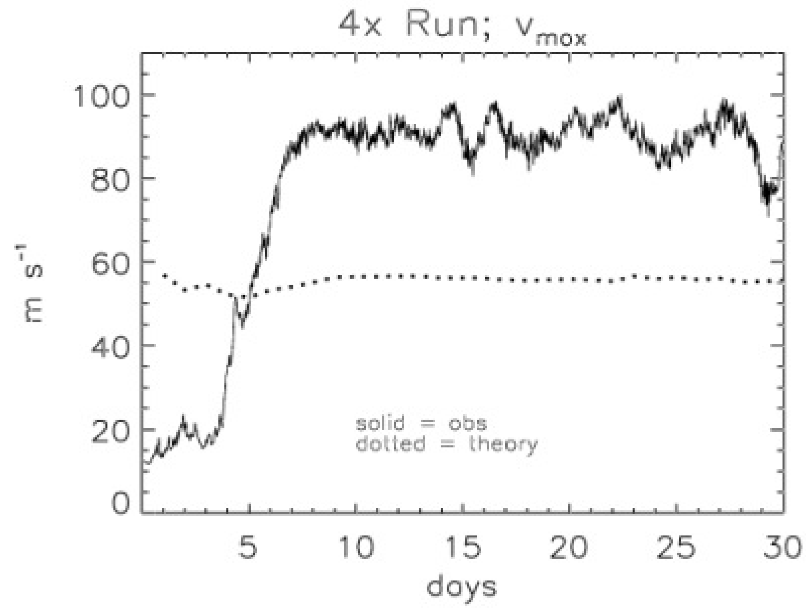

Figure 2: Observed maximum winds in a high-resolution (Δr = 4.25 km) run (one fourth the grid spacing as the default run; solid) and theoretical predictions using Emanuel's MPI theory (dashed).

Emanuel's MPI theory estimates the maximum possible intensity of a hurricane from limited knowledge of the sea surface temperature, outflow temperature, and boundary layer relative humidity, along with sensitivities to latitude (Coriolis effect), ambient surface pressure, and outer radius, in decreasing importance. Surface temperature is a fixed parameter of the model (along with latitude and ambient pressure). The outflow temperature may vary depending on the details of the circulation, yet the variation of this value from one resolution to another when supplied into the MPI theory is not sufficient to explain the resolution sensitivity of storm intensity. There is much ambiguity as to how to define the boundary layer relative humidity (BL-RH). The theory, describes BL-RH as the subcloud layer relative humidity in Emanuel 1989. Assuming a turbulent boundary layer, which seems reasonable at the high wind speeds of the hurricane boundary layer, and assuming this means that the boundary layer is well mixed in the vertical, then vapor mixing ratio and potential temperature may be considered constant in the subcloud layer. This implies that air will vary from saturation at cloud base to some minimum value of relative humidity just above the ocean surface. Rotunno and Emanuel (1987, hereafter RE87) used this minimum value to evaluate BL-RH. In the RE87 model we find that the lowest grid level in the model is saturated at the radius of the eyewall at all resolutions. Using this definition of BL-RH, we find that the BL-RH increases with increasing resolution since the saturated first grid level is found closer to the ground. This implies a weaker MPI at higher resolution. The MPI theory also requires that the BL-RH value be found at both the eyewall and in the environment. We find for our default run, as did Rotunno and Emanuel (1987) in their similar control run, that the BL-RH is approximately constant from the eyewall to the environment. In higher resolution runs, drier relative humidities are found in the environment than in the eyewall. The purpose of BL-RH in the MPI theory is to both model the vertical transfers of entropy from the ocean surface to the cloud base and to limit the parameter space of possible solutions by fixing the radial structure of pressure in the vortex from the eyewall to the environment. These applications of BL-RH are being reexamined in light of the model results.

IMPACT AND APPLICATIONS

Further work is needed to explain the results of the RE87 and E95a models and a paper is in preparation on this line of research. Based on our current findings we believe that the foundations for the Emanuel MPI theory need to be examined more critically. At first we will propose a cautionary note for a theory that has now gained wide acceptance in the meteorological community. Soon afterward we hope to develop a modification to the MPI theory, or propose an alternative that can be tested.

TRANSITIONS

During FY2001, we plan to continue our study of three-dimensional instabilities in hurricane vortices and plan to apply the stability analyses to 'real' hurricane data generated with full physics numerical models. A critical examination of the foundations of Emanuel's MPI theory will be completed and a new theory for predicting hurricane MPI will be initiated. Finally, the dynamics of a vertically sheared hurricane will be investigated using recent breakthroughs in vortex Rossby wave theory and vortex alignment.

RELATED PROJECTS

None.

SUMMARY

This year's work has focused primarily on:

a) analyzing the vortex-scale shear instability processes that transport angular momentum and heat into the core of the vortex;

b) re-examining the physics governing maximum hurricane intensity.

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